



U. S. NAVAL SUBMARINE MEDICAL CENTER

Submarine Base, Groton, Conn.

REPORT NUMBER 580

DECOMPRESSION PATTERNS DEVELOPED BY AN
INTERDEPENDENT ELECTRIC ANALOG

by

Gary P. Todd
Lieutenant, MC, U. S. Naval Reserve

Bureau of Medicine and Surgery, Navy Department
In-House Laboratory Research Work Unit MR011.01-5009.01

Approved and Released by:

J. E. Stark, CAPT MC USN
COMMANDING OFFICER
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Reviewed and Approved by:



Charles F. Gell, M.D., D.Sc (Med)
Scientific Director
SubMedResLab

Reviewed and Approved by:



Joseph D. Bloom, CDR MC USN
Director
SubMedResLab

Approved and Released by:



J. E. Stark, CAPT MC USN
COMMANDING OFFICER
Naval Submarine Medical Center

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SUMMARY PAGE

THE PROBLEM

To design and manufacture a simple, inexpensive electronic decompression analog.

FINDINGS

A simple electronic decompression analog was developed. The mathematical model of this analog differs somewhat from the Standard U. S. Navy modified Haldane model. In this analog the theoretical tissues of increasing effective half times are arranged in series as opposed to the Haldane model in which the tissues are in parallel. The application of simulated dives to this analog have resulted in decompression schedules which show interesting variation from Standard U. S. Navy Tables.

APPLICATION

Although the application of analog methods to decompression schedule requirements is not new, this model possesses some interesting areas to pursue where the currently used model has appeared to be inadequate. The simplicity of this analog further provides a simple and rapid method to observe the application of further modifications to this or the Haldane mathematical models. If this model proves successful on careful schedule testing, the analog could readily be used as a decompression meter in real or accelerated time.

ADMINISTRATIVE INFORMATION

This investigation was conducted as a part of In-House Independent Laboratory Research and Work Unit MR011.01-5009. The present report was approved for publication on 16 May 1969 and has been designated as Submarine Medical Center, Submarine Medical Research Laboratory Report No. 580. This is the final report on the work unit listed above.

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ABSTRACT

A simple, inexpensive electronic analog has been developed and constructed which is based on a modification to the classical Haldane mathematical model. Unlike the Haldane model this analog uses a series alignment of theoretical half-time tissues rather than the usual parallel arrangement. Schedules produced by this analog closely follow the experimental inert gas elimination curves developed by Behnke and the mathematical model theorized by B. A. Hills. The results raise an interesting question as to the adequacy of the present Haldane model modification employed by the U. S. Navy for decompression schedule calculation.

Further studies must be made before this latter question can be answered.

DECOMPRESSION PATTERNS DEVELOPED BY AN INTERDEPENDENT ELECTRIC ANALOG

INTRODUCTION

It is known that the classical Haldane model for calculating decompression tables had weaknesses in that it deviated from empirical data in short shallow dives and in prolonged or deep dives. In general, his model gave too long a decompression for shallow dives and too short in prolonged or deep dives. In practice, these weaknesses have been largely overcome by empirically modifying the tissue ratios allowed at varying depths, and by adding longer half-time tissues to the model.

It has also been known for some years that obese persons do poorly on long, deep dives, but that they appear to do much better than thin persons on short or shallow dives. This is usually interpreted as due to the slower fat tissues absorbing excess nitrogen from the fat tissues during decompression¹. This situation is not covered by the classical model.

In electrical terminology, the classical model is equivalent to a bank of independent capacitor-resistor circuits, with no spill-over between circuits (Diagram 1).

This study concerns the design and characteristics of a highly stable electrical model with interdependent connections (Diagram 2). Using this extremely simple analog, a new series of theoretical decompression schedules has been computed.

To get away from the term "tissue", which cannot be defined in this context and is therefore misleading, the term "rank" is employed to discuss the different capacitors. The analog discussed here has eight ranks; number 1 being nearest the power supply, and number 8 the last rank (Diagram 3).

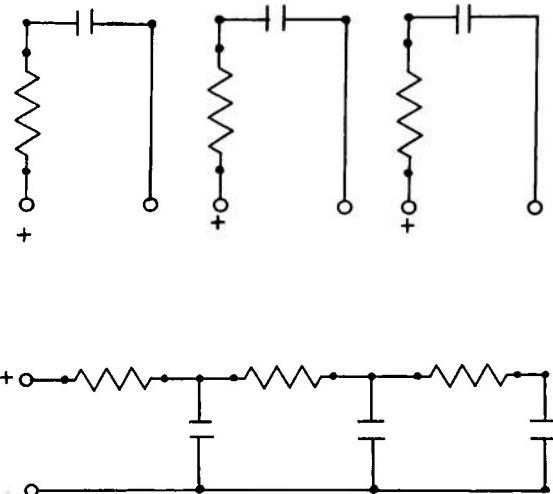
DESIGN

With the exception of the capacitors, and possibly the printed circuit boards, all of the parts used are readily available at modest cost (Parts List, Table I). The schematic is shown in Diagram 2.

TABLE I. PARTS LIST

Symbol	Item
	R ₁ Resistor, 1000 ohm, 1/2 watt, 10%
	R ₂ Resistor, 270K ohm, 1/2 watt, 10%
	R ₉ SRB Silicon rectifier bridge, capable of handling 100 PIV and 100 ma
	C ₁ -C ₉ 100 mfd, 35 vDC, electrolytic capacitors. Must be very low leakage, such as Mallory Tantalex (tantalum)
	SW Single-pole, single throw toggle switch
	Binding posts (12 needed)
	Printed circuit boards, 3 x 6", not sensitized, phenolic composition (5)
	Ferric Chloride etching solution, 500 cc
	Wire, 22 ga., Teflon insulation

Note: Total cost - less than \$15



SW-1 serves to isolate external power from any of the circuitry. SRB is a silicon rectifier bridge which may be a single integrated unit or individual components. It prevents damage to the polarized capacitors in case of accidental reversal of external power leads. R-1

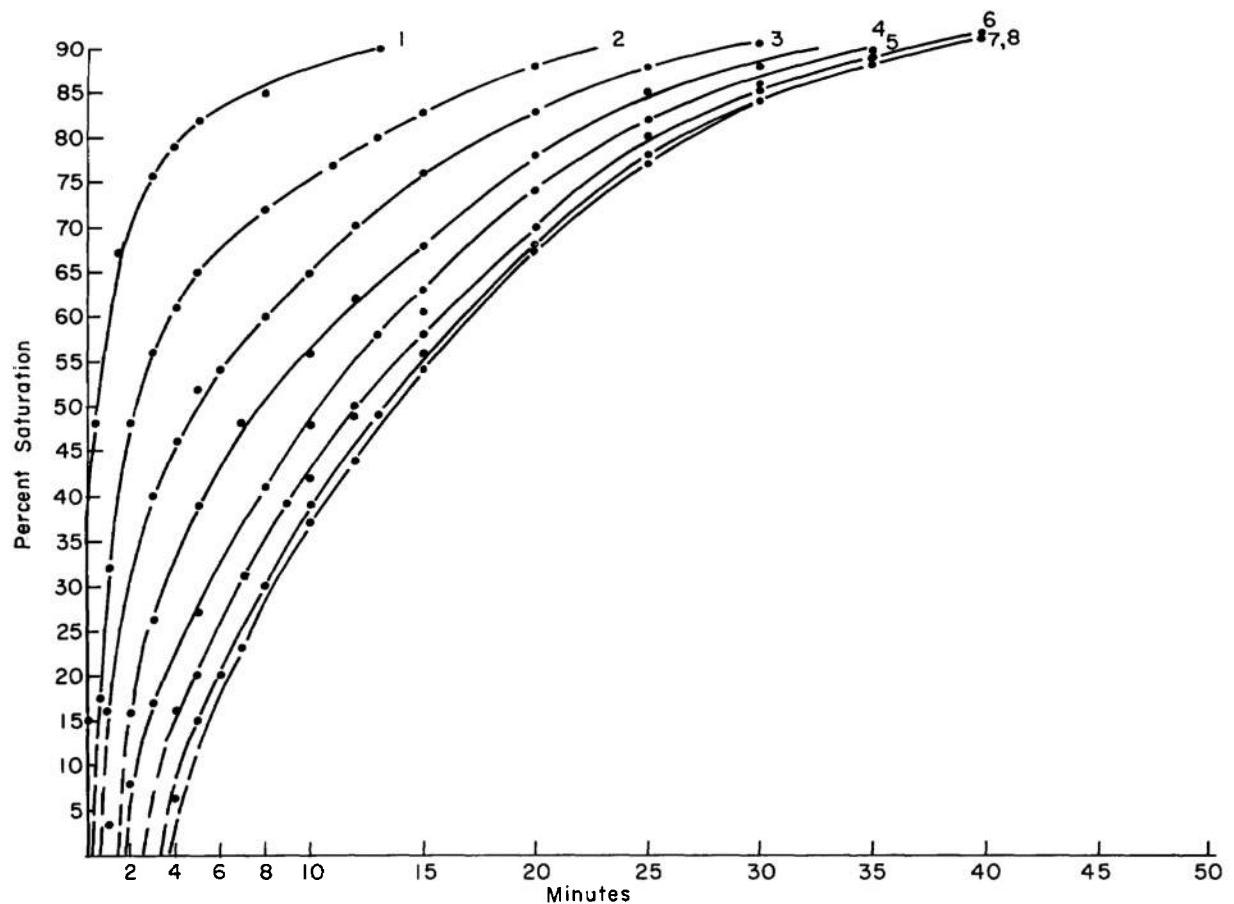
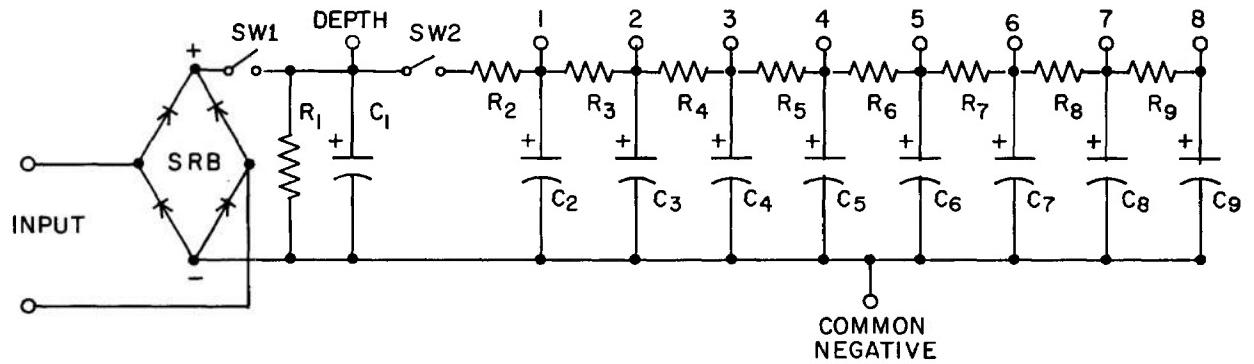


Figure 1—Saturation Pattern of Different Ranks of Analog. (Note how each rank appears to start saturation at different times, and how the last two ranks behave as one.)

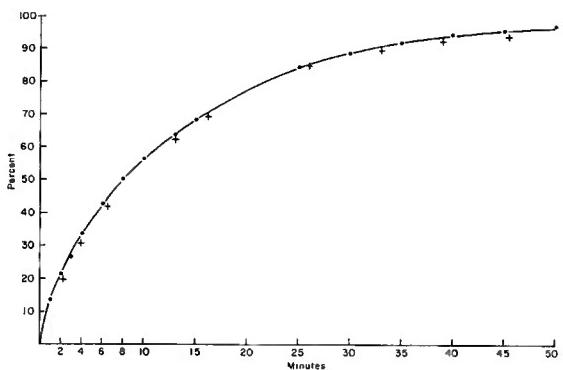


Figure 2—Integrated Curve from Figure 1. Plus marks give data from Figure 2 in "Behnke, A. R. and Willmon, T. L., Am. J. Physiol. 131:3, Jan 1941." Figure 2 is a plot of measured N_2 elimination. "+" Time Scale 1 :: 10.

is a relatively low resistance bleeder resistor which allows C-1 to discharge instantly when voltage is decreased, and also acts as a short-circuit across the analog capacitors (C^2-C^9) for their discharge during decompression. SW-2 isolates the voltage reference capacitor C-1 from the rest of the circuit during manipulation of external voltage, if desired. Both switches remain closed ("on") during actual runs. The rest of the circuit is rather straight-forward: R^2-R^9 are all $\frac{1}{2}$ watt, 270K ohm, 10% carbon resistors connected in series with the positive pole of the respective capacitors connected in parallel between them. Design of the circuitry with the positive pole of the capacitors between the resistors is a convenience feature, because many meters use a clip for the negative lead and a probe for the positive lead.

The only critical elements in the circuit are the capacitors. The ones used were chosen because of their high capacitance, small physical size, and excellent stability. Internal leakage is about 6% in 8 hours.

For convenience, ten 5-way binding posts are used to monitor voltages at each of the analog ranks and the depth reference voltage at C-1. One post is connected to the common negative ground of the analog section for the meter's negative lead.

Eight ranks were chosen because of cost—the entire budget for this project exclusive of power supply and meter being under \$50.00. Four more ranks would double the longest half-time to about 355 minutes in a 1 to 12 scale. As many as sixteen might be needed for a saturation dive.

TABLE II

Rank	Half-Time	Change in Half-Time
A.		
1	20 sec	20 sec
B.		
1	31	31
	65	34
C.		
1	33	33
	101	68
	132	31
D.		
1	33	33
	123	90
	192	69
	228	36
E.		
1	33	33
	130	97
	238	108
	310	72
	345	35
F.		
1	33	33
	134	101
	272	138
	390	118
	460	70
	498	38
G.		
1	33	33
	133	100
	290	157
	451	161
	565	114
	638	73
	677	39
H.		
1	33	33
	133	100
	297	164
	490	193
	648	158
	765	117
	840	75
	885	45

Table II shows saturation half-times for eight different analogs with from 1 to 8 ranks, respectively. Notice the effect of a rank on neighboring ranks, and especially note the importance of the last two ranks.

Figure 1 shows the saturation pattern of each of the ranks in an eight rank analog. These data were added together to obtain an integrated Figure 2. Superimposed on Figure 2 is Behnke's empirical curve of N_2 washout in man².

Figure 3 shows that the half-time changes with saturation. Figure 4 compared the classical model to the analog, with time scales adjusted so that both simultaneously saturate to 95%.

CALIBRATION OF THE ANALOG

By actual measurement, the analog saturates in about sixty minutes. Setting that equal to a saturation time of twelve hours gives a scale of 5 seconds to the minute.

TABLE III

Ratios of Absorbed Inert Gas (per analog) Upon Arriving at Various Stops. Data from 160/60 Dive.

Stop	Rank							
	1	2	3	4	5	6	7	8
50'	1.38	1.33	1.13	.89	.73	.60	.51	.48
40'	1.23	1.37	1.25	1.04	.90	.75	.66	.66
30'	1.19	1.36	1.36	1.24	1.16	.92	.81	.75
20'	1.07	1.21	1.28	1.28	1.23	1.17	1.19	1.16
10'	1.09	1.19	1.29	1.35	1.40	1.40	1.40	1.40

Below are "Surfacing Ratios" from Hills' data:

30'	1.57	1.60	1.67	1.70	1.73	1.76	1.76	1.79
20'	1.36	1.45	1.55	1.64	1.70	1.73	1.76	1.76
10'	1.12	1.21	1.30	1.36	1.42	1.48	1.51	1.55

Note that the simulated dive for a 30' last stop was three minutes longer, and for a 20' last stop was five minutes longer than Hills' actual titration times. This was done as an additional safety factor.

TABLE IV

Arriving Ratios from a 150/30 Table After a 30-Minute Dive.

Stop	Rank							
	1	2	3	4	5	6	7	8
20'	1.88	1.70	1.28	.98	.77	.64	.57	.55
10'	1.37	1.58	1.54	1.30	1.19	.91	.74	.72
0'	1.18	1.30	1.40	1.43	1.40	1.24	1.24	1.21

TABLE V
Same Decompression Schedule as in Table IV, but With Only 24 Minutes Bottom Time.
150/30 Table Used.

Stop	Rank							
	1	2	3	4	5	6	7	8
20'	1.79	1.59	1.13	.89	.70	.56	.53	.51
10'	1.30	1.41	1.40	1.28	.98	.81	.72	.67
0'	1.18	1.27	1.33	1.33	1.30	1.21	1.15	1.09

Using this time scale, and presaturating the analog to atmospheric nitrogen, B. A. Hills' data on decompressing from a 160/60 dive were run through the analog (Table III). Because of their careful titration they are used as a main source of hard data for calibration of the analog.

The ratios thus obtained were checked by running through the 150/30 schedule after a 30 minute dive and after a 24 minute dive. The former dive is considered borderline at best, while the latter is quite safe. The ratios for arriving at the different stops are given in Tables 4 and 5, respectively.

From these simulated dives, criteria were selected for tolerable inert pressures at each stop. These inert gas pressures are expressed as ratios of inert gas pressure to hydrostatic pressure. The ratio selected for use in the analog for all ranks and depths was 1.4:1.

Because Hills' data⁴ shows that under proper conditions the diver can surface directly from deeper stops, a surfacing pressure of 57 feet of nitrogen was used in all the analog predicted tables. This is equivalent to a 1.75:1 "surfacing ratio."

Ascent rates were set so as not to exceed a 1.6:1 ratio of absolute nitrogen pressure in the breathing mixture at diving depth to absolute hydrostatic pressure at the depth achieved at the end of a one minute ascent. One minute is chosen because it is approximately equal to normal blood circulation time.

An examination of the data in Table II will reveal why it was decided to return to the original Haldane concept of using the same ratio for all depths and all tissues, except for ascent and surfacing. For, although the ratios used for constructing the original tables varied from 3.4:1 down to 1.2:1, the

same dive simulated on the analog produces remarkably similar ratios for all ranks and depths. Until the decompression schedules predicted by the analog are actually tested, there can be no real advantage in juggling ratios.

RESULTS

Table VI gives decompression schedules from the analog using the criteria above. These are untested schedules, and are presented simply to show the pattern developed

when a different model is used in calculating the schedules.

The format is different in that ascent time is included in subsequent stops. No ascent time is more than one minute. For those dives which require a longer ascent, a non-stop "Stop" is given to indicate the point of ascent at the end of each minute during ascent. For example, 30/1 means to ascend to 30 foot stop in one minute and continue without stopping to the next stop; 0/1 means to come to the surface in one minute.

TABLE VI
Analog Tables.

Depth/Time	60	50	40	30	20	10	0	Total Time	Navy
40/200							1	1	.7
40/300						1	1	2	19.5
50/100						1	1	2	.8
50/120						4	1	5	5.7
60/60							1	1	2
60/120						5	2	8	26.8
70/50						2	3	1	1.2
70/60						5	2	1	9.0
70/120					1	10	5	1	17
80/40				2	3	2	1	8	1.3
80/60				2	6	2	1	11	18.2
80/120				2	15	9	1	27	74.0
90/30				2	5	0	1	8	1.5
90/60				4	9	0	1	14	26.3
90/120				6	24	30	1	61	101.2
100/30				4	4	0	1	9	4.5
100/60				4	9	3	1	17	38.3
100/90				7	20	5	1	33	84.2
100/120				10	60	24	1	95	132.2
110/30			1	5	5	0	1	12	8.7
110/60			4	4	15	0	1	24	55.5
110/90			4	6	25	24	1	60	107.3
120/30			2	13	0	0	1	16	15.8
120/60			4	6	17	0	1	28	70.5
120/90			5	10	45	29	1	90	131.5
130/30		1	1	4	9	0	1	16	22.8
130/60		1	3	6	18	0	1	29	85.7
130/90		4	4	12	76	24	1	121	153.5
140/30		1	5	3	9	0	1	19	28.0
140/60		4	4	8	29	0	1	46	96.8
140/90		5	6	16	88	24	1	140	166.0
150/30		1	5	3	12	0	1	22	34.2
150/60	3	3	3	12	23	24	1	69	111.8
150/90	3	4	8	20	100	24	1	160	—
160/30	3	0	3	5	12	0	1	24	40.2
160/60	4	3	4	11	36	30	1	89	132.0
160/90	4	4	10	26	104	24	1	173	—

These schedules are based on a 12 hour saturation time and thus are equivalent to a maximum half-time of about 180 minutes. This is probably adequate for the short dives included.

For comparison, the United States Navy Tables of 1963 are included in Table VII. Ascent time is included in the first stop.

Since the analog was calibrated to Hills' titration of the 160/60 dive, it is interesting to see what the analog predicts on that dive. Both dives are presently in Table VIII.

Finally, a table of no-decompression dives is given in Table IX.

DISCUSSION

This project was originally intended to see what type of decompression schedule profiles would develop if a model different from the classical model was considered. No attempt was or is made to correlate the ranks with anatomical sites.

TABLE VII
U. S. Navy Diving Tables.

Depth/Time	50	40	30	20	10	0	Total Time
40/200							.7
40/300					19.5		19.5
50/100							.8
50/120					5.7		5.7
60/60							1.0
60/120					26.8		26.8
70/50							1.2
70/60					9.0		9.0
70/120				4.8	47		51.8
80/40							1.3
80/60					18.2		18.2
80/120				18	56		74.0
90/30							1.5
90/60					26.3		26.3
90/120				33.2	68		101.2
100/30					4.5		4.5
100/60				10.3	28		38.3
100/90			4.2	23.0	57		84.2
100/120			13.2	41	78		132.2
110/30					8.7		8.7
110/60				19.5	36		55.5
110/90			13.3	30	64		107.3
120/30					15.8		15.8
120/60			3.5	22	45		70.5
120/90			20.5	37	74		131.5
130/30				4.8	18		22.8
130/60			10.7	23	52		85.7
130/90		9.5	19	45	80		153.5
140/30				7	21		28.0
140/60				17.8	23	56	96.8
140/90	3.5	14	18	42	88		166.0
150/30				10.2	24		34.2
150/60			4.8	19	26	62	111.8
150/90	None available						
160/30				4.2	11	25	40.2
160/60			11	19	33	69	132.0
160/90	None available						

TABLE VIII

Comparison of Analog Schedule with Hills' Titration
of 20 Foot Stop of Same 160/60 Dive.

Stop	Analog	Hills	U. S. Navy (1963)
60	4		
50	3	5	
40	4	8	11
30	11	19	19
20	36	55*	33
10	30	0	69
0	1		
TOTAL	89	87	132

*The analog was calibrated with 60 minutes at the 20 foot stop as a safety factor.

TABLE IX
No-Decompression Dives.

Depth	Limit	Ascent Rate
30	unlimited	0/1
40	200	10/1, 0/1
50	100	10/1, 0/1
60	60	10/1, 0/1
70	14	20/1, 0/1
80	9	20/1, 0/1
90	9	30/1, 20/1, 0/1
100	7	30/1, 20/1, 0/1
110	6	40/1, 20/1, 0/1
120	5	40/1, 20/1, 0/1
130	5	50/1, 20/1, 0/1
140	4	50/1, 20/1, 0/1
150	4	50/1, 20/1, 0/1
160	4	60/1, 20/1, 0/1

If anyone desires to build such an analog for his own evaluation, it is fair to warn him that changing the time scale will change the ratios developed. Initially, the machine was calibrated to a six hour saturation period. With that, the pertinent ratio was 1.6:1 instead of 1.4:1. However, the schedules produced for short dives were approximately the same.

Notice in Figure 1 the delay before the last ranks begin to saturate. In the time scale used, this means a delay of some 30-40 minutes before the last three ranks even begin to saturate. In the 160/60 dive, the last rank reached a peak of 60 feet about 30 minutes of decompression at the 20 foot stop. Thus, the last ranks frequently continue to saturate well into the decompression.

Figure 3 appears more complicated than it is. In it, the actual time for 50% and 90% saturation was measured. Then, assuming a simple exponential function, apparent times were calculated. If the saturation followed a simple exponential, the apparent values would fall on top of the measured values. Since they did not, it is shown that the apparent half-time is constantly changing with saturation. Clearly shown is that the half-time lengthens for the first four ranks, and shortens for the last three ranks. It does not change for the fifth rank.

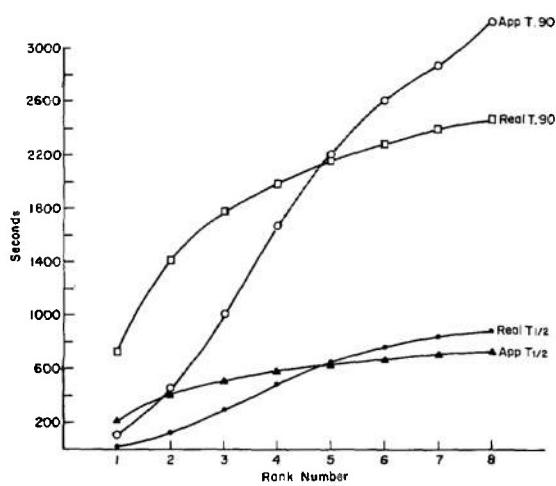


Figure 3—Measured Times of 50% and 90% Saturation. Also shown is apparent values if a simple exponential function is assumed and value is calculated from the other measured value.

In Table II, it is clearly shown that the last two ranks play an important role in the overall behavior of the analog. They behave as a dam beyond which the electrons cannot go, and therefore determine what the final voltage will be when the excess electrons in the foremost ranks leak out into the last ranks. If there are too few ranks, the average voltage levels high... and decompression is needlessly prolonged; too many, and shallow stops are made too short for a short dive, too long for a saturation dive.

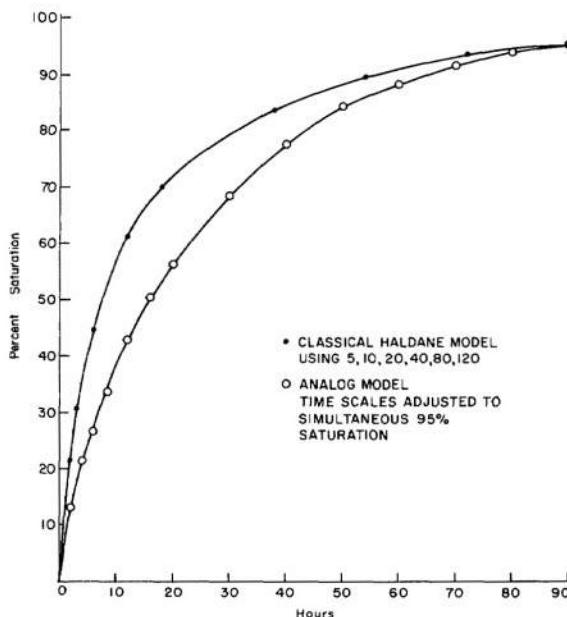


Figure 4—Left is Classical Haldane Model using 5, 10, 20, 40, 80, 120. Right is Analog Model, Time Scales Adjusted to Simultaneous 95% Saturation.

The present analog has too few ranks to be considered for a saturation dive. Figure 5 is presented to help any investigator trying to decide how many ranks to use in an expanded version. If the trend for the first eight ranks holds up, it can be expected that an analog using the same size resistors and capacitors with fourteen ranks would have a maximum half-time of 3000 seconds. This is equivalent to 500 minutes with the present time scale. Also, doubling the resistor size will double the half-time, and vice versa.

Notice that the surfacing ratios from the 10 foot stop in Table III are much lower than the ones from the 20 and 30 foot stops. When simulating this dive on the analog, it was noticed that the dive called for leaving the 20 foot stop at 33 minutes, while the voltages on the analog required an additional 3 minutes at the 20 foot stop. The voltage on rank 8 peaked at 60.5 feet, twelve minutes into the 20 foot stop, and remained there until 30 minutes into the stop, at which time it began to drop. Thus, eighteen minutes of the 20 foot stop are taken up for reversing the direction of flow, in spite of an 18 foot negative pressure gradient.

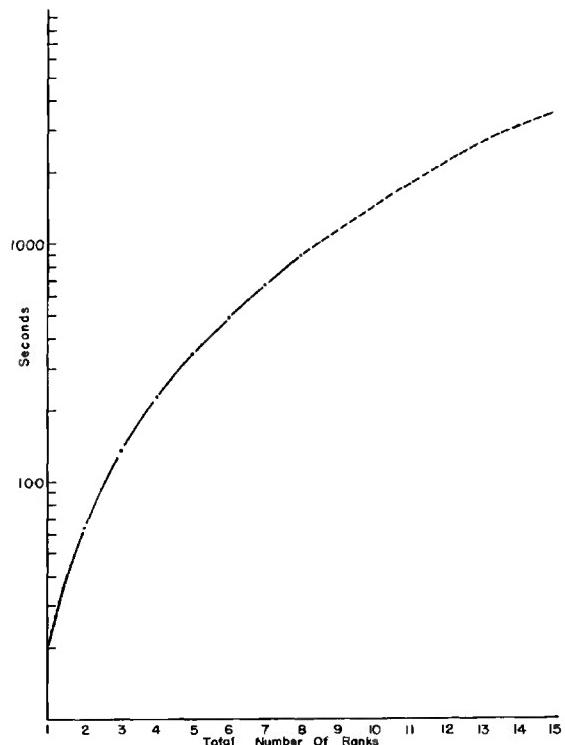


Figure 5—Longest Half-Time in Seconds Relative to Number of Ranks.

The lower ratios at 10 feet support B. A. Hills' contention that bubble phenomena exist at 10 feet. It does not support his argument that they exist at 20 feet, since the bubbles could have been formed by an abbreviated 20 foot stop. Indeed, the analog indicates that the standard 20 foot stop is too short by about 3 minutes. This may explain why some of his goats bent on the standard table.

From Figure 4, it is evident that the inter-dependent analog reaches 50% saturation later than the classical Haldane model. However, it reaches 100% saturation sooner. This works to the diver's benefit on short dives, but to his detriment on longer dives.

The most interesting finding is shown in Figure 2, where Behnke's empirical curve of nitrogen washout in man is superimposed on a summation of each rank's saturation. It is obvious that the fit is nearly perfect, and just as obvious that the classical model will not simulate this curve.

The diving tables predicted by the analog are very interesting, but appear to be unduly short. However, when compared with Hills' data, the analog predicted schedule comes out two minutes longer than his careful titration.

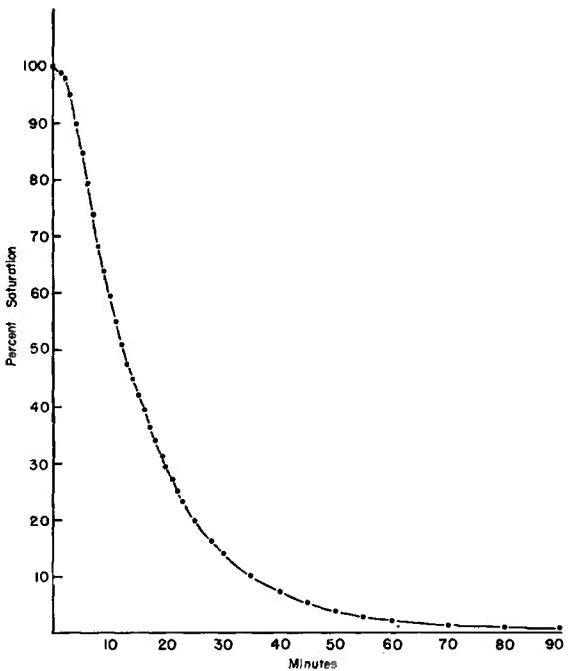


Figure 6—Desaturation of Rank #8.

And, if your attention is called to the 120/90 and 100/120 schedules which have similar decompression times in the U. S. Navy Standard Tables, you will see that the analog schedules are right in line. The analog schedules almost invariably have deeper stops, especially on longer dives.

Certain dives, namely 160/90 and 150/90, developed a "saturation pattern" which would make them much too short if human saturation occurs in much over 12 hours. Hesitation should be employed before using these two tables until a larger analog is tested. This pattern exists when the 20 foot stop is around 100 minutes and/or the 10 foot stop is for about 24 minutes, signifying that the last rank is controlling, and that there is no way to know if an additional rank would or would not control, if present. Another rank would mean longer stops than indicated by the present model.

This is what is meant by the previous statement concerning the importance of the last two ranks: their placement is just as critical as the choice of a dam site on a river, insofar as the diver is concerned.

The "No-Decompression" dives given in Table XI are very significant, since at the lower depths the analog has predicted precisely what is in the U. S. Navy Tables. The classical method does not predict these dives, and the tables were empirically derived, at least for the shallower depths. The deeper dives calculated by the analog are shorter than the Navy Tables because a longer dive would necessitate a stop at 20 feet under the criteria selected.

The question arises, considering saturation diving, whether the analog would behave any differently than the classical exponential model, since the analog would obviously be controlled by the last rank.

Figures 6 and 7 were obtained by saturating all ranks and then allowing them to discharge to zero. It is evident from Figure 7 that the last rank does desaturate by a simple exponential function. However, there is a delay in the analog of some 2.5 minutes before this desaturation begins. If the "tissue" under consideration for a saturation dive were 600 minutes half-time, would be equivalent to an extra wait of 150 minutes at the first stop before any desaturation would occur in the last rank. After that, a simple exponential function would apply just as in the classical model.

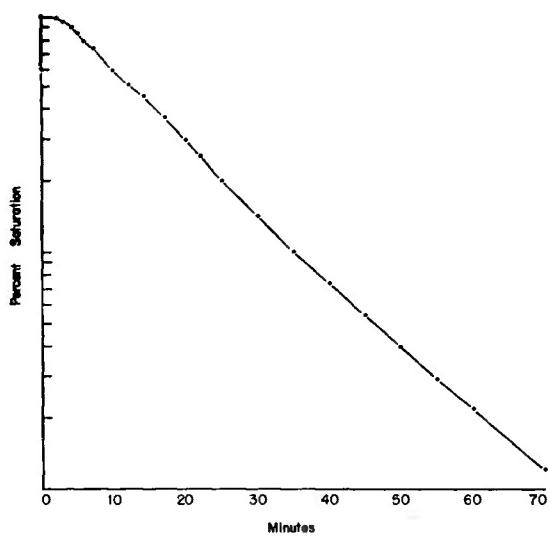


Figure 7—Semi-Log Plot of Figure 6. Notice delay of 2.5 minutes at onset.

With testing in practical applications there will come the inevitable modifications. Most obvious, of course, are the number of ranks and the ratios used. Although the present data would make it appear unnecessary, a hybrid model combining ideas of perfusion and diffusion could be easily constructed with separate diffusion analogs for each half-time "tissue." This is far beyond the scope or intent of the present paper.

An inexpensive and easily constructed electric analog has been described. It is firmly felt that further investigation using this as a tool in studying decompression illness and in designing decompression schedules is warranted and required.

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13. ABSTRACT A simple, inexpensive electronic analog has been developed and constructed which is based on a modification to the classical Haldane mathematical model. Unlike the Haldane model this analog uses a series alignment of theoretical half-time tissues rather than the usual parallel arrangement. Schedules produced by this analog closely follow the experimental inert gas elimination curves developed by Behnke and the mathematical model theorized by B. A. Hills. The results raise an interesting question as to the adequacy of the present haldane model modification employed by the U.S. Navy for decompression schedule calculation.

Further testing must be done before this latter question can be answered.

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